



Research Article

# Spatial Assessment of Soil Erosion Risk Using RUSLE and GIS in Dhumuga Watershed, Ambo, Ethiopia

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## Abstract

Soil erosion has become a critical problem leading to land degradation and environmental risks globally. To grasp the rates of soil loss and identify the main factors driving these issues, it is vital to examine the specific impacts of soil erosion across different locations. Therefore, between 2021 and 2023, a research initiative was undertaken to assess, rank, identify, and map sections of the watershed that are particularly susceptible to soil erosion. The RUSLE components for factors R, K, L, S, C, and P were integrated using the ArcGIS 10.4.1 spatial analyst's raster calculator tool to calculate and create maps that illustrate the risk and intensity of soil erosion in the Dhumuga watershed. The Dhumuga watershed was categorized into five groups based on average annual soil loss: 0–5 ton/ha<sup>-1</sup> year<sup>-1</sup> (very slight), 5–10 ton/ha<sup>-1</sup> year<sup>-1</sup> (slight), 10–20 ton/ha<sup>-1</sup> year<sup>-1</sup> (moderate), 20–50 ton/ha<sup>-1</sup> year<sup>-1</sup> (high), and > 50 ton/ha<sup>-1</sup> year<sup>-1</sup> (very high). The assessment of soil erosion severity was influenced by factors such as rainfall, soil type, DEM, land use, and land cover, employing the GIS-based RUSLE equation. The spatial risk of soil erosion was sorted into five categories based on severity, with 11.58% of the area categorized as very high risk (>50 ton ha<sup>-1</sup> year<sup>-1</sup>), and 54.2% in the very low to low-risk category. On average, the watershed yielded an annual sediment production of up to 13.94 tons/ha/year, which is within an acceptable range. Considering these research findings, GIS-based analyses can be utilized to pinpoint areas at risk of soil erosion and identify vulnerable zones, offering crucial insights for future soil conservation and model enhancement.

## Keywords

Dhumuga-Watershed, Erodibility, Erosivity, Land Use Change, GIS

## 1. Introduction

Land degradation is a major issue in sub-Saharan African nations, with Ethiopia particularly suffering from this phenomenon, which has resulted in a significant drop in agricultural productivity [1, 2]. This situation leads to the loss of productive soil due to water erosion (an onsite effect) and the siltation affecting downstream communities and reservoirs

(an offsite effect), presenting a serious obstacle for the nation [3]. Soil erosion, which refers to the removal and movement of solid particles from the soil surface by water, is a crucial aspect of land degradation that calls for sustainable land use and soil management solutions to tackle this problem [4, 5].

The soil erosion rate induced by water exceeds the ac-

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ceptable annual threshold of 11 tons per hectare per year [6]; with the national average soil loss estimated at 12 tons per hectare per year, and particularly severe rates of 300 tons per hectare per year observed in steep slope areas with little vegetative cover [7]. Additionally, research conducted in the Huluka Watershed, located in the West Showa Zone, indicated that soil loss varied from 14.4 tons per hectare per year to as high as 27 tons per hectare per year, reflecting a concerning rate of erosion [8]. Soil erosion due to water was also identified as a critical issue during a focused group discussion in the Dhumuga Watershed [9]. In this watershed, water-related soil erosion accounted for 46% of the identified problems [9]. Therefore, conducting an erosion hotspot assessment at the watershed level is considered vital for creating soil conservation strategies for sustainable development in the region [10].

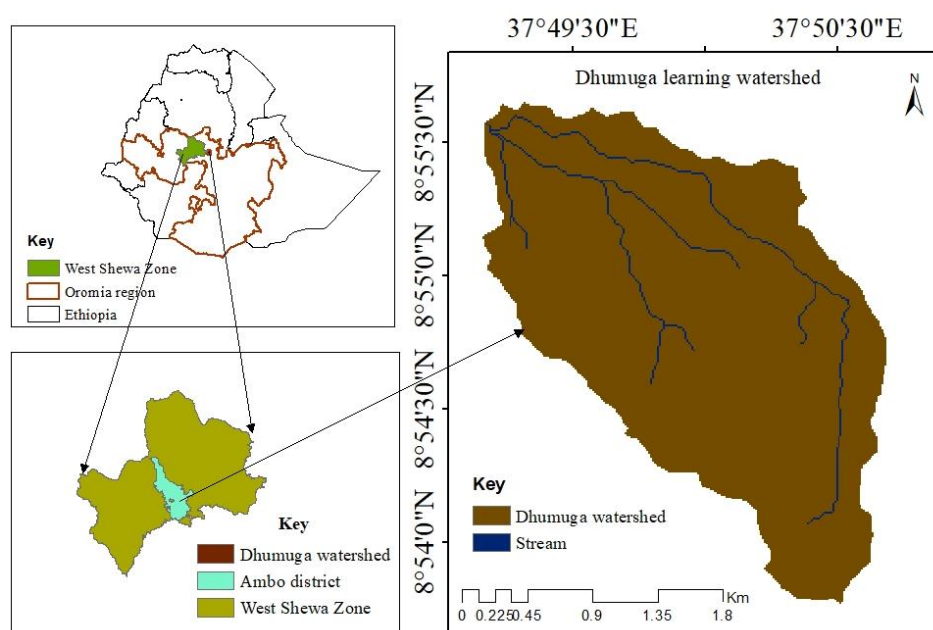
In Ethiopia, soil preservation has become a crucial focus, aimed at sustaining and boosting agricultural output while reaching food self-sufficiency, which aligns with the long-

term objectives of the agricultural development program. This study was conducted to assess, prioritize, identify, and map soil erosion hotspots in the newly defined Dhumuga watershed using RUSLE and GIS technologies, providing essential qualitative and quantitative data to enhance future intervention efforts.

## 2. Materials and Methods

### 2.1. Study Area

The was conducted from 2021 – 2023 in Dhumuga watershed that found in West Shewa Zone. Geographically, it is located between 8°40'30" N-8°59'30" N and 37°40'30" E-37°52'0"E latitude and longitude, respectively (Figure 1) and covers a catchment area of 564.25ha.



**Figure 1.** Location Map of Dhumuga learning watershed.

### 2.2. RUSLE Model and Soil Erosion Calculation

#### *Determination of RUSLE Factors*

The revised universal soil loss equation (RUSLE) has been employed for this investigation [11]. The model is considered the updated version of the proto USLE model [12]. It has been recognized as the most widely used empirical model to assess soil erosion loss, to estimate soil erosion risk and to guide soil conservation plans to control soil erosion [13, 14]. The RUSLE layers derived for R, K, L, S, C, and P fac-

tors were integrated within the raster calculator tool of the ArcGIS 10.4.1 spatial analyst in order to quantify and generate soil erosion risk and severity maps for Dhumuga watershed.

The general equation for USLE is [15]:

$$A = R * K * L * S * C * P \quad (1)$$

Where A is the computed soil loss, R is the rainfall runoff erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the cover management factor, and P is the supporting practices

factor. This empirically based equation, derived from a large mass of field data; computes combined inter rill and rill erosion using values representing the four major factors affecting erosion. These factors are climatic erosivity represented by R, soil erodibility represented by K, topography represented by LS, and land use and management represented by C and P.

### 2.3. Rain Fall Erosivity (R) Factor

The extent and intensity of every rainfall throughout a year are justified by rainfall erosivity (R) factor. For this study, satellite Rainfall Data of GPM (Global Precipitation Measurement) were used. This data is the product of NASA (National Aeronautics and Space Administration) and is widely used because of its enhanced accuracy [16]. The annual rainfall data for Ambo meteorological stations situated near to the watershed were obtained from the Ethiopian Meteorological Authority (EMA), it was integrated with the satellite data to validate the results. In this study, the R-factor was calculated using the proposed model of [17] by utilizing the given equation from the interpolated map of rainfall.

$$R = 0.05 * P \quad (2)$$

Where P shows average annual rainfall (mm)

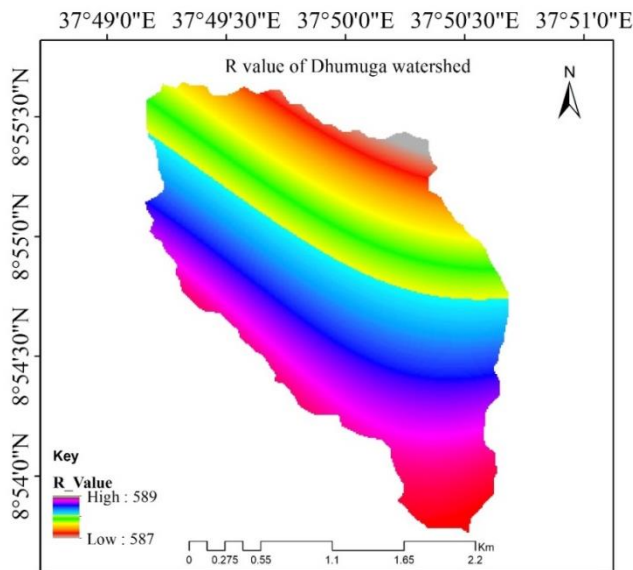


Figure 2. Erosivity factor map of the study area.

### 2.4. Soil Erodibility Factor (K Factor)

The soil erodibility factor, known as the K factor, is determined by factors such as soil texture, structure, organic matter, and probability. A soil survey was carried out in the watershed, considering slope steepness, slope aspect, and soil color, resulting in the collection of 36 soil samples that were

then combined into 22 composite samples. These samples were examined for their soil textural class using the hydrometer method and for organic matter using the Walkley-Black method. Consequently, employing the equation derived by [18], the soil erodibility factor (K-value) was computed for each soil sample, and a soil erodibility map was created (Figure 3) as raster data through interpolation using the inverse distance weighted (IDW) method.

$$K = [2.1 M 1.4 \times 10^{-4}(12 - a) + 3.25(b - 2) + 2.5(c - 3)]/100 \quad (3)$$

where, M particle Size parameter; (percent silt + percent very fine sand) (100–percent clay), a = Percent organic matter, b = permeability class, c = soil structure code used in soil classification.

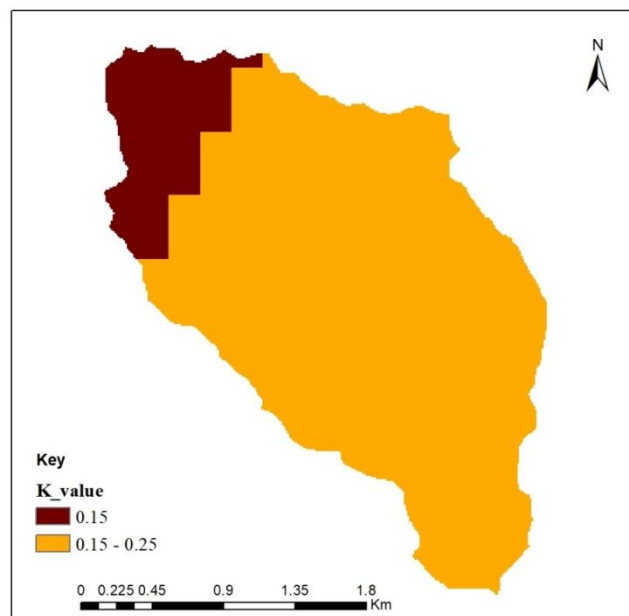


Figure 3. Map of soil erodibility factor of the study area.

### 2.5. Slope Length (LS Factor)

The L and S factors represent the effects of slope length (L) and slope steepness (S) on soil erosion. LS- factor was calculated by unit stream power erosion and deposition (USPED) method, which uses the raster calculation flow accumulation and slope of watershed [19]. The following equation was used:

$$LS = \text{power} ("flow accumulation" * [cell resolution]/22.1, 0.4) * \text{Power} (\text{Sin} ("slope in degree" * 0.01745))/0.09, 1.4) * 1.4 \quad (4)$$

A Landsat image captured in 2021 underwent pre-processing and classification for land use and land cover using both Arc GIS 10.8 and ERDAS IMAGINE 2021 through a supervised

classification approach. The topographic factors (LS) illustrate the impact of slope length (L) and slope steepness (S) on soil erosion. Slope steepness affects flow velocity, while slope length indicates the distance from the erosion origin to the site of deposition [20]. To eliminate depressions, the original 30m x 30m resolution Digital Elevation Model (DEM) was filled, and computations for flow direction, flow accumulation, and slope in degrees were performed within the ArcGIS environment.

$$LS = \left(\frac{AS}{22.13}\right)^{0.6} (\sin B / 0.0896)^{1.3} \quad (5)$$

Where, LS is slope steepness-length factor, AS is a specific catchment area, i.e. the upslope contributing area per unit width and B is the slope angle. LS factor was computed in ArcGIS raster calculator using the map algebra expression in Eq. (5) as suggested by [21].

LS value showed variations, hence, the Central and North Western part of the watershed has relatively flat, having lower LS value than the other part (Figure 4).

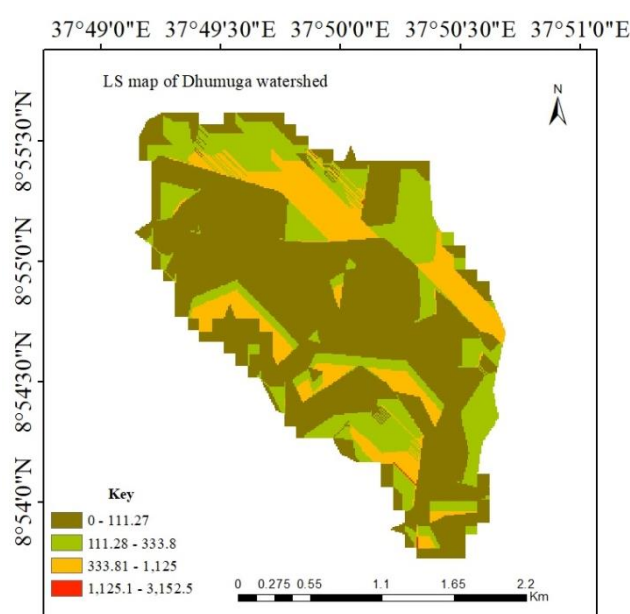


Figure 4. LS value Map of the study area.

## 2.6. Cover and Management (C) Factor

The C-factor serves to illustrate how cropping and management practices influence erosion rates. It is the most commonly utilized factor for comparing the relative effects of management options within conservation plans. The C-factor indicates the impact of the conservation plan on the average annual soil loss and the temporal distribution of that soil loss potential during construction activities, crop rotations, or other management approaches.

The watershed was categorized into various major land use types. C-values provided by different researchers for

these land use types were employed to map and estimate the weighted C-values for the catchment, which were then utilized in the USLE model. Support practices influence erosion mainly by altering the flow patterns, gradient, and direction of surface runoff while also decreasing both the amount and rate of runoff. The C factor values, adapted for conditions in Ethiopia, were applied in this study to derive the C-value. Based on the C-value estimates attributed to varying land uses, a support practice factor map was created by reclassifying the land use type map with the aid of spatial analysis tools in ArcGIS. The watershed was segmented into distinct sub-watersheds based on hydrological responses, which were then prioritized according to the mean annual soil loss rates of each sub-watershed; higher priorities were assigned to sub-watersheds experiencing greater mean soil loss rates, while those with lower rates received lower priority. An erosion severity classification was also developed using the mean annual soil loss data documented in the sub-watersheds. The tolerable rate of soil loss is recognized as 11 tons per hectare per year. [6].

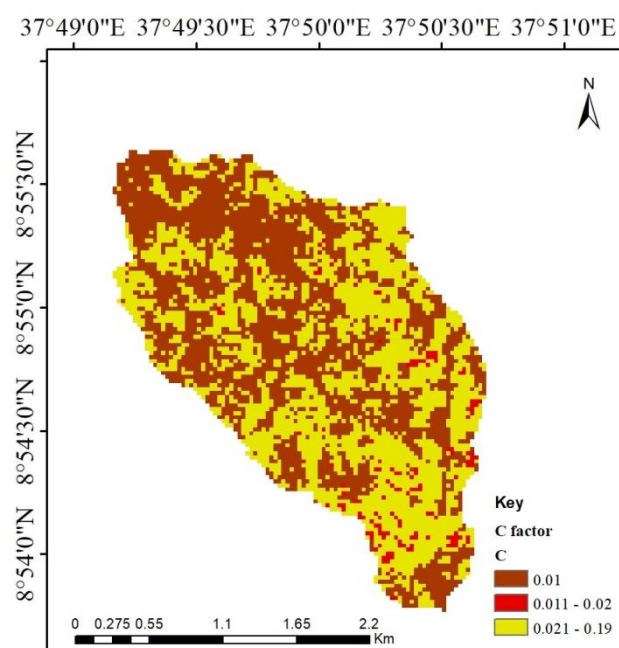


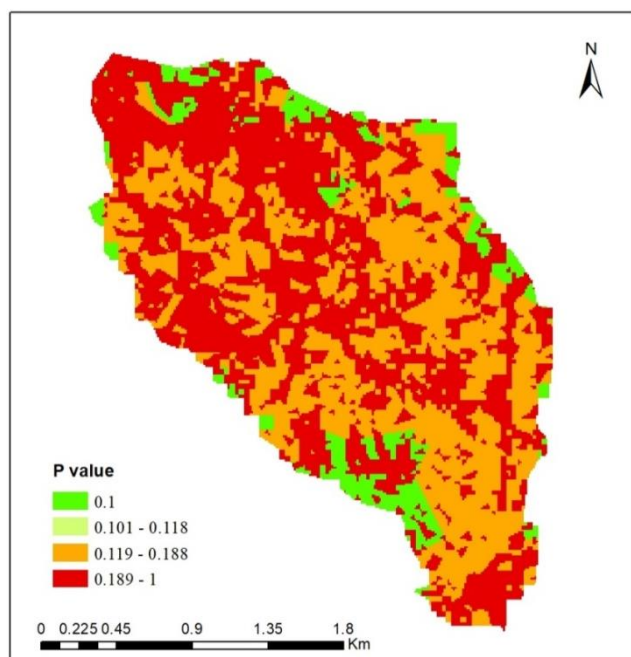
Figure 5. C value Map of the study area.

## 2.7. Erosion Management (Support) Practice (P) Factor

According to various scholars such as [12, 22, 23], the P-factor reflects the ratio of soil loss after implementing conservation measures to that from conventional row cultivation along the slope. Conservation strategies like contour farming, strip cropping, and terracing primarily influence water erosion by altering the amount, pattern, gradient, or direction of surface runoff, thereby decreasing both the volume and speed of runoff [11]. The P-factor varies between 0 and 1



[24]; a value close to 0 signifies effective conservation practices, while a value nearing 1 indicates inadequate conservation efforts. In the studied region [see Figure 6], the watershed lacks proper soil and water conservation initiatives. The land management practices present in the watershed are sub-par, making it impractical to assess soil loss based on the current conservation approaches. The watershed has been classified into five erosion management categories, as outlined by [24].



**Figure 6.** Erosion management practice (P) factor value Map of the study area.

### 3. Results and Discussion

RUSLE is the most utilized model for estimating soil erosion [25-27]. Furthermore, the RUSLE model's effectiveness is evident in its ability to predict soil loss with minimal information, which is particularly beneficial in developing nations where data is limited [28, 29]. The integration of GIS with soil erosion models has been employed to assess both the intensity and spatial distribution of erosion. Erosion of the study area [30]. For the current study, five different erosion factors including rainfall erosivity, slope length and steepness, land cover management, soil erodibility, and soil conservation were determined.

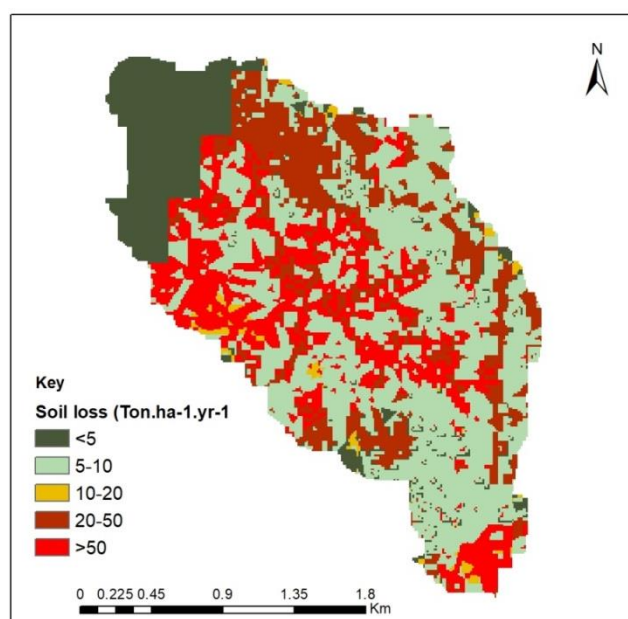
#### *Soil Erosion Losses in Dhumuga Watershed*

The annual soil loss was ultimately estimated by fully integrating the RUSLE model within a GIS environment. The rate of soil loss was derived from all the layers of RUSLE factors (R, K, LS, C, and P) that were previously generated. Each layer was formatted in a grid structure with a cell size of 12.5 meters. The layers were merged by multiplying the

corresponding cells from each layer based on the relationships specified by the RUSLE model. In order to produce the final soil erosion risk map, ArcGIS 10.4.1 Spatial Analyst Tool and the raster calculator were employed. The Dhumuga watershed was categorized into five classes based on mean annual soil loss, ranging from 0–5 ton/ha-1 year-1 (very slight), 5–10 ton/ha-1 year-1 (slight), 10–20 ton/ha-1 year-1 (moderate), 20–50 ton/ha-1 year-1 (high), to > 50 ton/ha-1 year-1 (very high), as shown in Table 1 and Figure 7.

**Table 1.** Soil loss in Dhumuga watershed.

Erosion categories	Soil loss (tons/ha/year)	Area in ha	Percentage
Very low	<5	78.43075	13.9
Low	5-10 ton	227.39275	40.3
Moderate	10-20 ton	150.65475	26.7
High	20-50 ton	42.4316	7.52
Very high	>50 ton	65.34015	11.58



**Figure 7.** The spatial distribution of soil loss in Dhumuga watershed.

The study area classified in to five classless that remained continuous in the different erosion class. Greater than 11% of the study area remained in higher severe erosion risk class. The proportion area at very low, low and moderate risk of erosion is 13.9%, 40.3% and 26.7% respectively, while the space between the moderate and very high erosion risk, around 7.5%, indicate a chance increasing. As indicate in the table (Table 1), around 11.58% of high, very high and severe

risk zones need soil and water conservation structures to reduce the risk of soil erosion. The mean erosion rate high in agricultural lands, followed by grazing lands, shrubs and forest lands, the highest soil erosion rates observed in the steep slopes. This study reveals the erosion rate higher in agricultural lands in line with [30-35].

Similar study in Ethiopia indicates that soil erosion by water represents a major threat to the long-term productivity of agricultural and water bodies where the estimated soil erosion rates range from  $16 \text{ t ha}^{-1} \text{ y}^{-1}$  to as much as  $300 \text{ t ha}^{-1} \text{ y}^{-1}$  [36].

## 4. Conclusion and Recommendation

The severity assessment of soil erosion GIS-based RUSLE equation considering rainfall, soil, DEM, land use, and land cover. The spatial soil erosion risk categorized into five classes based on its severity, and 11.58% of the study area found under very high risk ( $>50\text{-ton ha}^{-1} \text{ year}^{-1}$ ), 54.2% of the area remained in a very low to low-risk zone. In average, Dhumuga watershed generated an average annual soil loss up to  $13.94 \text{ ton/ha/year}$ , which is under tolerable range. But the simulated soil loss rate of some watershed areas exceeds the maximum tolerable soil losses rate ( $18 \text{ tons/ha/yr}$ ). This indicates that soil erosion is a serious problem in the study area watershed and adjacent similar areas.

The areas with high elevation along with prompt rainfall are susceptible to soil erosion. The study area with high to very high soil erosion warrant special priority and soil erosion control measures. However, this model forms a basis on mapping and prediction using remote sensing and GIS-based analysis for soil erosion risk area/vulnerable zones, such studies suggested for soil conservation and refining the model in the future.

## Abbreviations

DEM	Digital Elevation Model
EMA	Ethiopian Meteorological Authority
ERDAS	Earth Resource Data Analysis System
GIS	Geographic Information System
GPM	Global Precipitation Measurement
NASA	National Aeronautics and Space Administration
RUSLE	The Revised Universal Soil Loss Equation
USLE	Universal Soil Loss Equation
USPED	Unit Stream Power Erosion and Deposition

## Conflicts of Interest

The authors declare no conflicts of interest.

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